Efficient generation of high-energy quasi-monoenergetic ion beams using laser-induced cavity pressure acceleration

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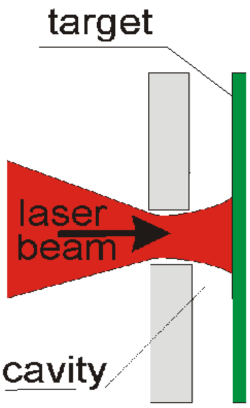
Results of 1D particle-in-cell (PIC) simulations are presented for the recently proposed laser-induced cavity pressure acceleration (LICPA) scheme in the regime of high radiation pressure. In LICPA the target foil is placed inside a cavity, and the laser beam irradiating the target is introduced into the cavity through an aperture. It is shown that using a circularly polarized laser pulse of intensity ~ 10^{21} W/cm^2 and a picosecond duration, irradiating a thin carbon foil placed in a cavity, quasi-monoenergetic carbon ion beams are obtained with average ion energies more than twice as high as those obtained without the cavity enhancement. PIC simulation results are compared with the predictions of the laser-sail model generalized to incorporate the cavity reflections, and an interesting and surprising agreement is found.

One of the important issues in the laser-driven ion acceleration is the efficiency of the laser-to-ion energy conversion. In this note we consider the problem of improving this parameter by "recycling" the energy of the incident laser pulse. The idea is to put the solid target inside a cavity, into which the laser beam is introduced through an aperture. The presence of the cavity should result in redirecting a substantial part of the reflected laser light back onto the main target, thus increasing the amount of laser energy converted into the energy of accelerated particles. This proposition is motivated by the success of such an approach - called the laser induced cavity pressure acceleration (LICPA) - in accelerating dense plasma projectiles using high-energy (≥100J) sub-nanosecond laser pulses at sub-relativistic laser intensities, where it was found to be almost an order of magnitude more efficient than the conventional ablative acceleration mechanism [1]. This was mainly due to the plasma pressure buildup in the cavity, but the increased laser absorption caused by the presence of the cavity also played a role. A possible realization of the LICPA approach in the radiation pressure regime is schematically shown in Fig. 1.

To obtain a quantitative estimate of the effectiveness of the new scheme we performed a 1D particle-in-cell (PIC) simulation of the laser interaction with a target consisting of a fully



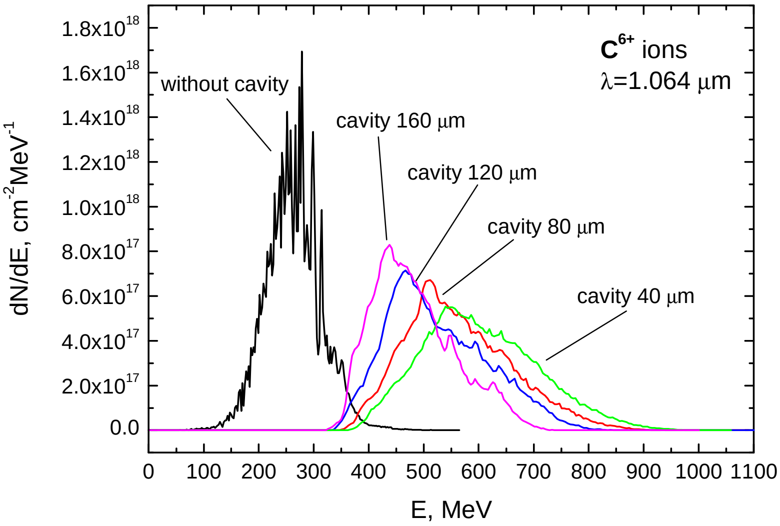


Fig. 1. A schematic drawing of a foil target with a barrier forming a cavity, designed to redirect a substantial part of the incident laser light back onto the target.

Fig. 2. Ion energy spectra at a distance of 150 µm from the target, obtained in a 1D PIC simulation for a 2 µm carbon target irradiated by a 2 ps laser pulse with intensity 2.5×10^{21} W/cm^2, without cavity reflection (black curve) and with cavity length varying from 40 µm to 160 µm. The reflection coefficient on the inner cavity wall was assumed to be $R_c = 0.64$.

ionized carbon plasma forming a 2 µm thick homogenous layer with the ion number density $n_i = 10^{23}$cm^{-3}, with an exponential pre-plasma layer on the front side of the target with the density gradient scale length equal to 0.25 µm. We considered a circularly polarized laser beam, since in this case the laser-plasma interaction is much more regular due to the absence of the oscillating component in the ponderomotive force. We assumed that the laser pulse has wavelength of 1.064 µm, a super-Gaussian profile $I(t) = I_L{\cdot}\exp(-t^6/\tau^6)$, with $I_L = 2.5\times10^{21}$ W/cm^2, and FWHM equal to 2 ps. The laser light reflected from the carbon foil back towards the laser is assumed to be partially reflected from a "mirror" placed at a distance L_c from the foil in the upstream direction, and redirected back towards the carbon foil (several further reflections may occur). The reflection coefficient for the radiation intensity was assumed to be $R_c = 0.64$. Simulations were done for the cavity length L_c varying in the range 40-160 µm. In Fig. 2 we show energy spectra of the accelerated ions measured at the distance of 150 µm from the original target, for various values of the cavity length, compared with the case when there is no cavity (i. e. $L_c = +\infty$). These spectra are rather narrow, which shows that the reflections inside the cavity do not spoil the narrow energy spread of the ion beams generated by the circularly polarized pulse. We see that the energy distribution is shifted towards higher energies as the value of L_c is decreasing, but this dependence is not so strong.

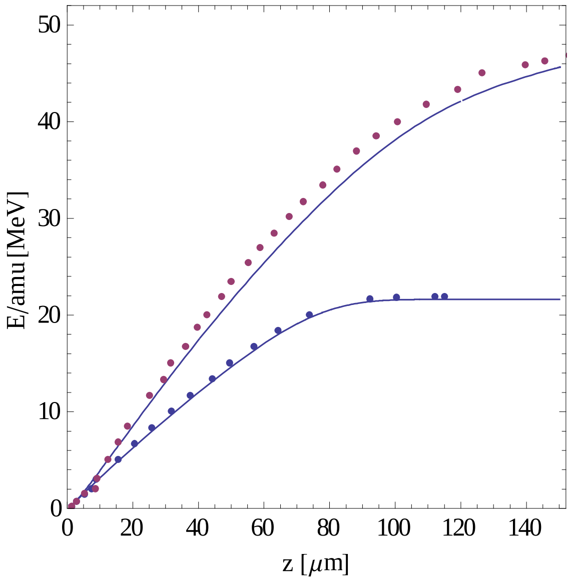


Fig. 3. The average ion energy per amu, as a function of the acceleration length, as predicted by the 1D PIC simulation for a 2 μm carbon target irradiated by a 2 ps laser pulse with intensity 2.5×10^{21} W/cm^2, without cavity reflection (lower set of dots) and with cavity length of 80 μm (upper set of dots). The reflection coefficient on the inner cavity wall was assumed to be R_c = 0.64. Continuous lines indicate predictions of the laser-sail model.

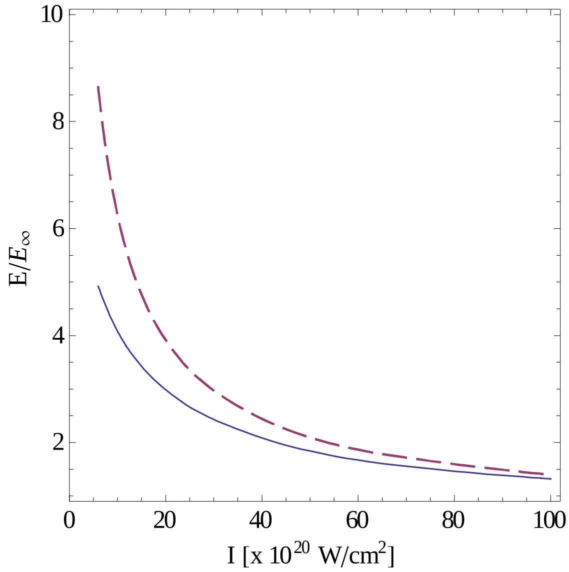


Fig. 4. The cavity enhancement factor for the average ion energy, as a function of the laser intensity, as predicted by the laser-sail model for a 2 μm carbon target irradiated by a 2 ps laser pulse with intensity 2.5×10^{21} W/cm^2, with an 80 μm long cavity. The lower continuous curve corresponds to the reflection coefficient R_c = 0.64, while the upper dashed curve corresponds to R_c = 0.81. Energies were determined at the distance of 500 μm from the target.

The effect of the cavity enhancement may be also illustrated by plotting the average ion kinetic energy per amu as a function of the acceleration length (defined as the distance travelled by the laser-plasma interaction front), as shown in Fig. 3 for L_c = 80 μm. In this case it is found that at the distance of 150 μm the average ion kinetic energy per amu is 47 MeV, compared to 22 MeV obtained without the cavity reflections. This translates into the laser-to-ion conversion efficiency of 42%, compared to 20% efficiency predicted by the 1D PIC simulation without the cavity.

Our PIC simulation shows that the accelerated plasma remains spatially localized, so it is also interesting to compare the results with the predictions from the light-sail (LS) model [2]. The equation of motion for a foil of mass density ρ and thickness d being accelerated by a radiation pressure of a laser pulse with the intensity $I(t)$ may be conveniently written in the form

(1) $$\frac{\gamma}{1-\beta}\frac{d\beta}{dw}=\frac{2I(w/c)}{\rho d c^3}$$

where $\beta = v/c$, $\gamma = (1 - \beta^2)^{-1/2}$, and $w = ct - x$ is the retarded time variable. In this formulation it is straightforward to incorporate the effect of reflections inside the cavity. Let us denote by w_j the values of w for which the laser pulse reflected from the foil strikes the cavity wall at the origin of the coordinate system for the j-th time. We may then define a sequence of functions $x^{(j)}(w)$ with $j = 1, 2....$, representing the position of the foil for w in the interval $[w_{j-1}, w_j]$, and a sequence of functions $e^{(j)}(w)$ representing the total laser energy incident on the foil, expressed in units of half of the relativistic rest energy of the foil. We assume $w_0 = 0$, $x^{(1)}(0) = L_c$; then $w_1 = 2L_c$, and more generally $w_{j+1} = w_j + 2x^{(j)}(w_j)$. Given $e^{(j)}(w)$, the relativistic speed is then given by $\beta^{(j)}(w) = \left[(1+e^{(j)}(w))^2 - 1\right] / \left[(1+e^{(j)}(w))^2 + 1\right]$, and $x^{(j)}(w)$ may be determined by integrating the equation $dx/dw=\beta/(1-\beta)$. We then have

$$(2) \qquad e^{(j+1)}(w) = e^{(j)}(w_j) + \frac{2}{\rho d c^3}\int_{w_j}^{w} I(w'/c)\,dw' + R_c \cdot \frac{e^{(j)}(w^{(j)}(w)) - e^{(j)}(w_{j-1}))}{(1+e^{(j)}(w^{(j)}(w)))(1+e^{(j)}((w_{j-1})))},$$

where R_c represents the reflection coefficient from the inner cavity wall. The function $w^{(j)}(w)$ gives the value of the retarded time from the interval $[w_{j-1}, w_j]$ characterizing the ray which after reflection from the accelerating foil strikes the inner cavity wall at the instant w belonging to the interval $[w_j, w_{j+1}]$. This set of formulas allows us to determine the position and the kinetic energy of the foil in a recursive way. The areal density of our carbon foil including the pre-plasma was $\rho d = 4.573$ g/m^2. As may be seen in Fig. 3, the predictions for the foil ion energy per amu as a function of the acceleration length obtained from the LS model are in surprising agreement with the PIC results. We verified that this interesting agreement holds for the full range of cavity lengths considered here. Assuming that this agreement would hold also for other values of the laser intensity, we may analyze the dependence of cavity enhancement factor on the laser intensity. As shown in Fig. 4, this factor may be as large as 5 at the intensity of 5×10^{20} W/cm^2, but it is decreasing with increasing intensity.

References

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